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Marine Fouling and Thermal Dissipation of Undersea Wireless Power Transfer

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ADMINISTRATIVE INFORMATION

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EXECUTIVE SUMMARY

This report describes the thermal effects and marine fouling on an undersea wireless power transfer system. The coils used in this wireless power transfer (WPT) experience elevated temperatures because of the resistive losses in the wire. Urethane and epoxy prevent water intrusion, but are thermal insulators and can lead to coil failure. Several different coating strategies to both protect the coils against seawater and dissipate the generated heat are investigated. In addition, the rise in temperature can increase the likelihood of marine biofouling on the exposed coil surfaces. A biofouling study on the wireless power transfer coils and whether there might be increased microbial growth as a result of the power transfer is also explored. The main benefit to the study provided here is to begin to gain an understanding of the effects thermal and marine fouling would have on WPT efficiency. The analysis will show that handling the heat should be a priority when implementing a high-power WPT system for unmanned underwater vehicles (UUVs). Coils must be carefully designed to dissipate the heat buildup but still maintain good transfer efficiency. Fortunately, the analysis will also show that the elevated temperatures on the coils is at a biocidal level, effectively killing off any marine microbes.

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1. INTRODUCTION

The desire to increase the mission duration of undersea unmanned vehicle (UUV) operations necessitates the need to recharge these vehicles in situ. The two techniques currently used to recharge UUVs without extraction implement either an electric socket or rotary transformer [1, 2]. Unfortunately, both of these techniques require precision mating for the transfer of electrical energy. For the electrical socket configuration, any physical misalignments can lead to shorting or corrosion of the conductors used in the power transfer. The rotary transformer approach addresses issues with exposed conductors; however, alignment on the order of millimeters is required for efficient power transfer. In practice, this degree of alignment is difficult to achieve for deployed underwater systems. Other challenges for both systems are biofouling and silting, which can prevent close contact required for efficient power transfer. Wireless power transfer (WPT) is a solution that can alleviate the close contact requirement.

Researchers are actively exploring wireless power transfer for charging UUVs within the maritime environment [3-5]. The benefits of using WPT are its ability to achieve greater stand-off distances and transfer power levels greater than 1kW. However, several open questions must be addressed before WPT can be integrated into operational maritime systems. First, although WPT can achieve high transfer efficiency, resistive losses in the wire generate heat in the coils through Joule heating. Transfer and receive coils must be developed that can either operate at elevated temperatures or efficiently dissipate the generated heat. Second, the mechanisms which influence levels of biofouling on wireless power transfer systems are not completely understood. The elevated temperatures generated by WPT coils, along with increased mission durations, provide a favorable environment for marine microbial growth. It is critical to determine if marine fouling will reduce WPT efficiencies. Additionally, microbial growth may lead to coil misalignment or greater stand-off distances, which would further reduce power transfer efficiency.

This report investigates how thermal behavior and marine biofouling affect the energy transfer for undersea WPT systems. Specifically, this study focuses on the transmitter and receiver coils used for the wireless transmission, since these are the only components of the system that are in direct contact with the seawater, where thermal dissipation and potential fouling is of concern. The authors of this report expect the coils to operate at elevated temperatures as heat is generated in the power transfer process. For a typical power transfer of 1000 W, at least 10% of the power will be dissipated as heat. This study therefore focuses on a thermal dissipation of up to 100 W. Space and Naval Warfare Systems Center Pacific (SSC Pacific) researchers explored multiple material compositions for encapsulating the coils to determine the best one for dissipating the generated heat. Finally, the effects of heating on marine fouling are studied to determine if a relationship exists between elevated temperatures and an increase in microbial growth on the coils.

2. THERMAL DISSIPATION TESTS

SSC Pacific researchers performed tests to investigate the thermal dissipation capabilities of the charging coils for a magnetically coupled wireless power transfer (recharging) system. The target energy transfer rate for the charging system was 1000 W. An efficiency of 90% was assumed, meaning that 100 W of thermal dissipation would be dissipated as heat to the ambient environment from the transmit coil. For underwater WPT, the ambient environment is the ocean, which provides an excellent heat sink for the heat dissipation. To measure the thermal dissipation capabilities of candidate coil configurations, mock-ups of the transmit coil were made where the coil itself was replaced with resistive elements, as shown in Figure 1. These mock-ups consisted of 14 resistors (2.5 ohms) in series, for a resistance of 35 ohms. The geometry of the thermal testing coils included an outer diameter of 5 inches, an inner diameter of 3.5 inches, and a thickness of 0.75 inches.

Figure 1. Thermal coil with polyurethane.

To provide a robust and waterproof housing for the coil mock-ups, we potted the coils in a polyurethane material used for many underwater sensors and electronics package systems at SSC Pacific. This potting material was "Polyurethane HMP 85-1 Slow Splicing and Molding Compound" by Fluid Polymers. It is a two-part polyurethane and is amber in color with a listed service temperature range from –51 to +149 ºC. The density of the compound is 1.09 g/cm3, however, the manufacturer did not provide thermal conductivity and specific heat information. Based on previous testing, SSC Pacific researchers were concerned that the thermal conductivity of the polyurethane might be too low to allow sufficient heat transfer to the water to prevent overheating. Therefore, we selected an additional potting material for testing specifically designed to provide a high thermal conductivity while maintaining the electrical insulation and waterproofing required. This second material was "Thermally Conductive Epoxy, 832TC" by MG Chemicals®, which uses aluminum oxide in a two-part black epoxy matrix. The constant service temperature range is –30 to

+140 ˚C, the density is 1.83 g/cm3, the thermal conductivity is 0.682 W/(m*K), and the specific heat is 1.9 MJ/(m3*K).

2.1 HEAT TRANSFER ANALYSIS

To determine the merit for using these different materials and geometries, SSC Pacific researchers conducted an analysis of the heat transfer for the coils. We modeled the encapsulated resistor chain as a problem of cylinder heat transfer, since in cross section it has a cylindrical geometry (Figure 2). Equation (1) provides the equation for cylindrical heat transfer:

$$\dot{Q} = \frac{(T_2 - T_1)}{R_{total}} where: R_{cylinder} = \frac{\left(\ln\left(\frac{r_2}{r_1}\right)\right)}{(2 \cdot pi \cdot L \cdot k)}, R_{convection} = \frac{1}{(h \cdot Area)}, R_{total} = R_{cylinder} + R_{convection} \quad (1)$$

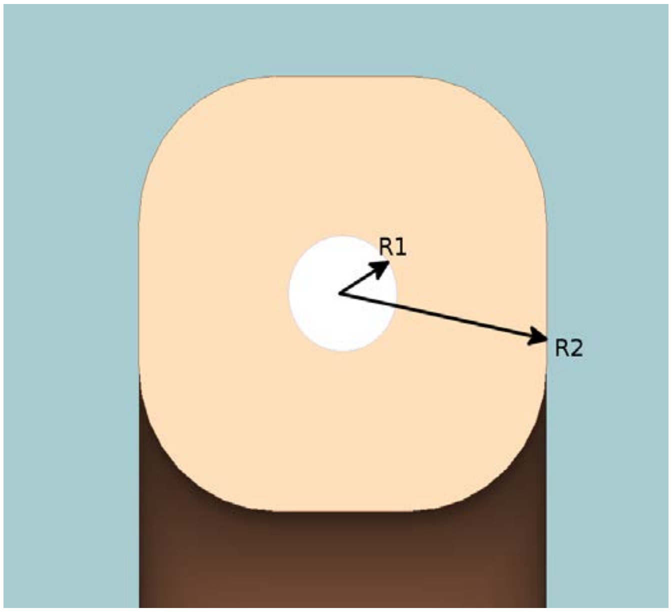

Figure 2. Thermal model of coil.

The inner radius of the cylinder, r_1, is equal to the resistor radius, 0.1 inch, and the outer radius, r_2, is half the ring thickness, 0.375 inch. The length, L, is equal to the mean circumference of the toroid, 13.35 inches. We assumed the resistors to be at a uniform constant temperature. We compared two cases, the polyurethane potting material and the 832TC thermally conductive epoxy.

Table 1 lists the thermal conductivity of suitable materials for underwater WPT, and Table 2 lists representative values of the convective heat transfer coefficients. The thermal conductivity of the MC Chemicals® 832TC is 0.682 WK/m, the polyurethane is 0.2 WK/m, and the convective heat transfer coefficient for the water interface is assumed as 80 WK/m^2.

Table 1. Thermal conductivity for coil materials.

Material	Thermal conductivity, k (W/m K)
Ferrite	3.3
Mineral Oil	0.162
Alumina, AD-85	16
Aluminum	205
Air	0.024
Water	0.58
Urethane	0.2
Thermal conductive epoxy, 832TC	.682
Glass	0.96

Table 2. Estimated convective heat transfer coefficients.

Fluid	Heat transfer coefficient, h (W/m K)
Water	80
Mineral oil	22

For the cylindrical geometry, the temperature differential corresponding to a 100-W heat transfer rate is given in the last column of Table 3. The total thermal resistance with 832TC is 1.53, which requires a 153 ºC temperature differential (for 100-W heat flow), whereas the total resistance with polyurethane is 3.72, which corresponds to a 372 ºC difference.

Table 3. Thermal resistance of heated toroid.

Ring material	$R_{cylinder}$	R_{water}	R_{total}	ΔT (C) for 100W
Urethane	3.10	0.62	3.72	372
832TC epoxy	0.91	0.62	1.53	153

The main contributor to the thermal resistance is the potting material, and since the thermally conductive epoxy (832TC) is about 3.5 times more (thermally) conductive than the urethane, the temperature differential is substantially reduced.

2.2 HEAT TRANSFER TESTS

To investigate the thermal dissipation, thermal coil mock-ups were potted in the polyurethane material and the "Thermally Conductive Epoxy, 832TC." Figure 3 shows the two coils. The toroid coil (TC) epoxy coil is on the left, and the polyurethane coil is on the right.

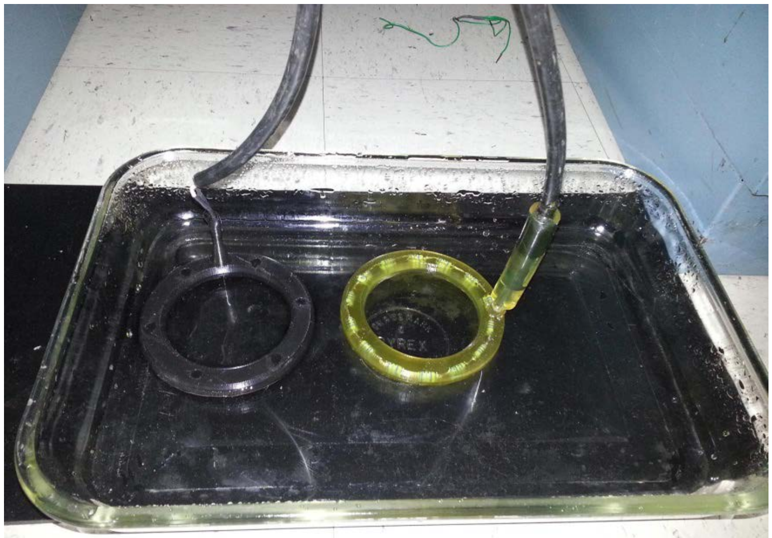

Figure 3. Thermal coils in pan of water.

The SSC Pacific researchers adopted a simple testing procedure to study the thermal behavior of the system. We applied an external voltage across the coils from an external power supply, and we monitored the temperature of the coils using an infrared (IR) camera. The camera used was a FLIR® Systems model FLIR® i7. An autostep down transformer (Variac) controlled the voltage across the coils. Initial testing was performed in air; however, the temperature rise was significant even at low power levels. To test the coils at higher voltage levels, we placed the coils in a shallow pan of water with the water level set to about one-half of the coil's thickness. That is, the bottom half of each coil was in water, while the upper half was not submerged. This allowed a clear view for the infrared camera that was not attenuated by the water since water can absorb the IR energy. Figure 4 shows the thermal signature of the coils using the FLIR® i7.

Figure 4. Thermal imaging using FLIR® camera.

For the first test, with the coils not submerged in water, the autostep down transformer (Figure 5) was set at 10%. This level produced a 13.6 VAC output, and the power dissipated in coil was $V^2/R = 5$ W.

Figure 5. Autostep down transformer.

The results from the FLIR® i7 indicated maximum temperatures for the TC epoxy and polyurethane coils, in air, of 34.4 and 39.1 °C, respectively. See Figure 6.

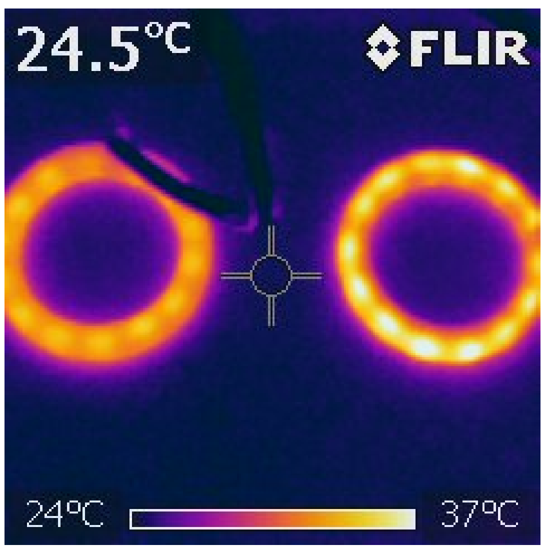

Figure 6. FLIR® image at 5 W in air.

Water was then added to the pan to bring the water level up to one-half of the height of the coils. The autostep down transformer setting was unchanged at 13.6 VAC output. The FLIR® i7 indicated the water temperature was 23 °C and indicated maximum temperatures for the TC epoxy and polyurethane coils as 30.9 and 37.6 °C, respectively. See Figure 7. As expected, the water acted as a heat sink, and reduced the coil maximum coil temperatures by several degrees. Note that the TC epoxy coil temperature dropped more than the polyurethane coil.

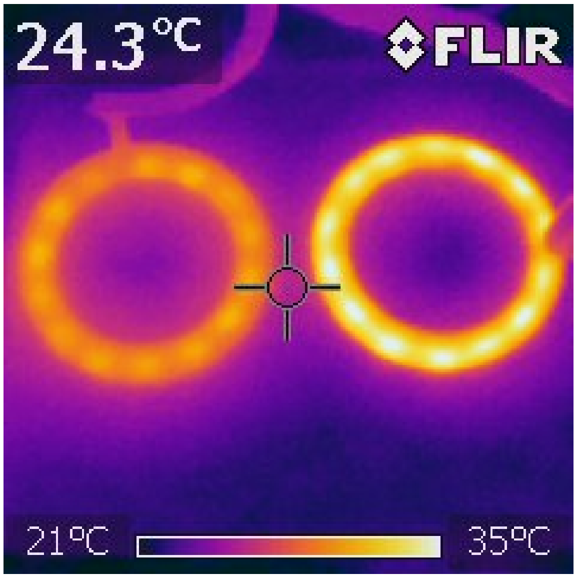

Figure 7. FLIR® image at 5 W in water.

The autostep down transformer was next set to output 28.4 VAC, which increased the power dissipated in the coils to 23 W. The FLIR® i7 maximum temperatures for the TC epoxy and polyurethane coils to be 53 and 70 °C, respectively. See Figure 8.

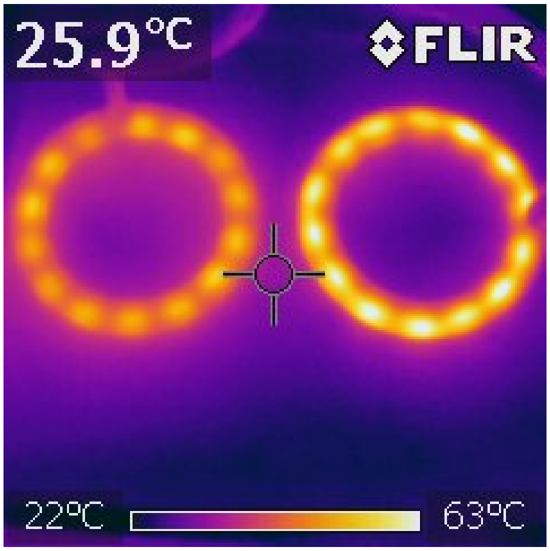

Figure 8. FLIR® image at 23 W in water.

For the third test, the autostep down transformer was set at 56.1 VAC output and the power dissipated in the coil was 90 W. The polyurethane coil exceeded 90 °C in 30 sec, and we stopped the test. The polyurethane coil overheated, as evidenced by the potting material melting shown in Figure 9.

Figure 9. Polyurethane thermal coil damage.

Due to the failure of the polyurethane coil, we only performed the remaining testing on the thermally conductive epoxy coil. The water depth was increased until most, but not all of coil was submerged. Specifically, the upper right quadrant was not covered to provide a spot for the FLIR® where the water would not attenuate the IR signal. This area of the coil reached 108 °C, but the portion of the coil submerged was less than 100 °C since no boiling water was observed on the coil. The FLIR® readings of the coil temperature where it was submerged are not accurate indications of the actual coil temperature since the water attenuates the infrared. See Figure 10.

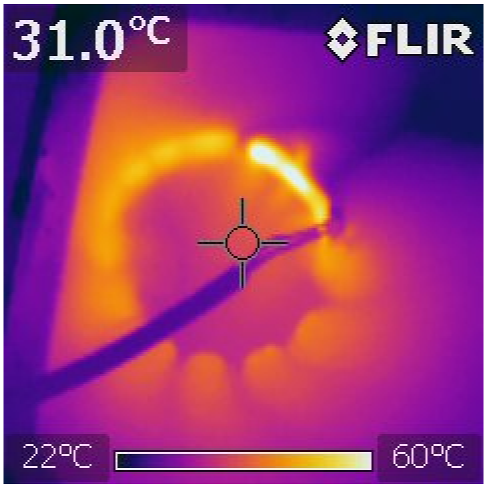

Figure 10. Thermally conductive epoxy coil at 90 W.

Table 4 summarizes the results of the findings on the thermal dissipation test on the coils. For this particular coil geometry, the thermally conductive epoxy, 832TC, should provide sufficient thermal conductivity to dissipate 100 W of power.

Table 4. Results of heat dissipation tests.

Power (W)	ETC Coil Max. Temp. (˚C)	Urethane Coil Max. Temp. (˚C)	Water Temp. (˚C)
5 (in air)	34.4	39.1	-
5	30.9	37.6	23
23	53	63	-
90	108	Fail	<100

3. MARINE FOULING TESTS

SSC Pacific researchers prepared four rings with polyurethane and prepared two rings with a copper-based, anti-foul paint intended for boat hulls. Figure 11 shows the four rings mounted to a frame for immersion in the San Diego Bay. Figure 12 shows two thermal conductivity epoxy rings, one with anti-foul coating. In our test, we applied power to the resistors through a ground fault interrupt (GFI) from the 120-AC power line. The first attempt to heat the coils failed because the polyurethane was overheated by the current through the resistors at the 100-W level. The polyurethane softened to the point that a conductive path developed to the seawater and the GFI tripped. This occurred within a few minutes after power was applied.

Figure 11. First ring test (rings on right have anti-foul coating).

To create a viable system for testing, four coils potted in MC 832TC were implemented in a similar testing configuration. Since this encapsulated material has a thermal conductivity of 0.682 WK/m (which is 341% greater than the polyurethane and about 17% greater than water) based on the previous thermal tests, we anticipated that we would avoid the thermal failure with the polyurethane. However, when the new coils were immersed in the San Diego Bay, and power was applied to heat them, one of the units was tripping the GFI in less than 1 day. By the end of the first week, all the units would trip the GFI. We determined that all of these TCE rings had developed conductive paths to seawater with resistances of 6 to 20 kΩ. Close examination of the units did not reveal any defects such as cracking or melting, and the root cause of the fault remained unclear.

Figure 12. Thermal conductive epoxy rings. Ring on right has anti-foul coating..

The thermal conductive epoxy (TCE) rings were left in place in the seawater unheated so the long-term marine fouling tests could be completed. The fouling test with the TCE rings was continued with four rings, two uncoated and two with the anti-foul boat paint applied. Figures 13 and 14 show the same rings shown in Figure 11 after 45 days of immersion in San Diego Bay. These results can be compared with Figures 15 and 16, which show the TCE rings without the anti-foul paint. We concluded from these tests that without taking some anti-fouling measures, the rings would have very significant fouling. The anti-foul paint was significantly effective in this case.

Figure 13. Bottom view of rings with anti-foul coating after 45 days.

Figure 14. Top view of rings with anti-foul coating after 45 days.

Figure 15. Bottom view of rings (no anti-foul coating) after 45 days.

Figure 16. Top view of rings (no anti-foul) after 45 days.

HEATED FOULING TESTS

A key part of the fouling characterization was determining the effect of heat on the marine fouling. For the heated fouling test, a modified testing technique was required, given the electrical failure of the TCE rings described previously. We implemented glass jars filled with mineral oil and containing heating resistors. These jars operated for 45 days with no shorting to seawater. Figures 17 and 18 show, respectively, a jar with no coatings and a jar with anti-foul paint applied. These jars were used as the controls. Three additional jars were prepared, each with a power cable penetrating through a watertight lid, and a chain of resistors immersed in mineral oil inside, that is, the jars were filled with mineral oil and the string of resistors immersed in the mineral oil. The resistors had a total series resistance of 150 ohms, and hence would generate about 100 W of heat when 120-VAC power was applied. One of the heated jars had the anti-foul boat paint applied, while the other two had no coatings. Figure 19 shows the control jar in Figure 17 after immersion in San Diego Bay for 45 days. Figures 20 and 21 show the two heated, uncoated jars after a 45-days immersion. The heating significantly reduced the fouling. Figure 22 shows the jar with the anti-foul boat paint applied but no heating after a 45-day immersion, and Figure 23 shows the jar with both 100-W heating and anti-foul boat paint after 45 days in San Diego Bay.

To quantify the relative amount of fouling, the weight of the jars at the end of the 45-day immersion was measured and tabulated in Table 5. The weights immediately after removal from the San Diego Bay (wet weight) and after drying for 5 days (dry weight) are shown. While the anti-foul paint and heating were both effective for controlling fouling of the coils in this experiment, the combination of both yielded the best results.

Table 5. Jar weights after 45-day fouling test.

Description	Weight (wet) grams	Weight (dry) grams
Control	542.9	451.0
Anti-foul paint only	526.0	445.2
Anti-foul paint and heating	452.0	440.0
Heating only #1	471.0	448.7
Heating only #2	469.5	445.5

Figure 17. New jar.

Figure 18. New jar with anti-foul coating.

Figure 19. Jar with no heating and no anti-foul coating after 45 days.

Figure 20. Jar 1 with heating (no anti-foul coating) after 45 days.

Figure 21. Jar 2 with heating (no anti-foul coating) after 45 days.

Figure 22. Jar with anti-foul coating (no heating) after 45 days.

Figure 23. Jar with anti-foul coating and heating after 45 days.

The results from the fouling tests indicate that heating the surface with 100 W of thermal load and anti-foul paint were very effective in preventing fouling. However, it is important to note that heating alone was nearly as effective as the anti-foul coating in preventing the fouling.

4. HIGH-POWER COIL SET

SSC Pacific researchers knew they needed a robust solution for the prototype system charging coils. The requirement was for materials that are waterproof, can withstand elevated temperatures, and are electrically insulating and thermally conductive. Many ceramics meet these specifications, and for the following analysis, we choose the ceramic alumni, AD-85, from Coors Ceramic Company. Coors Ceramic makes this material in various shapes (including custom shapes), and hence is a good candidate for the prototype WPT system.

The prototype design for the 1000-W system is illustrated in Figure 24 (the transmit direction is down). This design uses a spiral wound coil of approximately 12 turns of large-gauge Litz wire mounted on a ceramic disk of alumina. The alumina provides electrical isolation and thermal conductance. A layer of ferrite material constrains the magnetic field to minimize the losses caused by eddy currents generated in any nearby metal structures, such as the aluminum hull of a UUV. A thermally conductive encapsulant waterproofs and electrically insulates the entire assembly. For this prototype, we chose a polyurethane resin, TC-2920F, over the previously tested epoxy, 832TC, as it proved to provide better waterproofing of the electrical system.

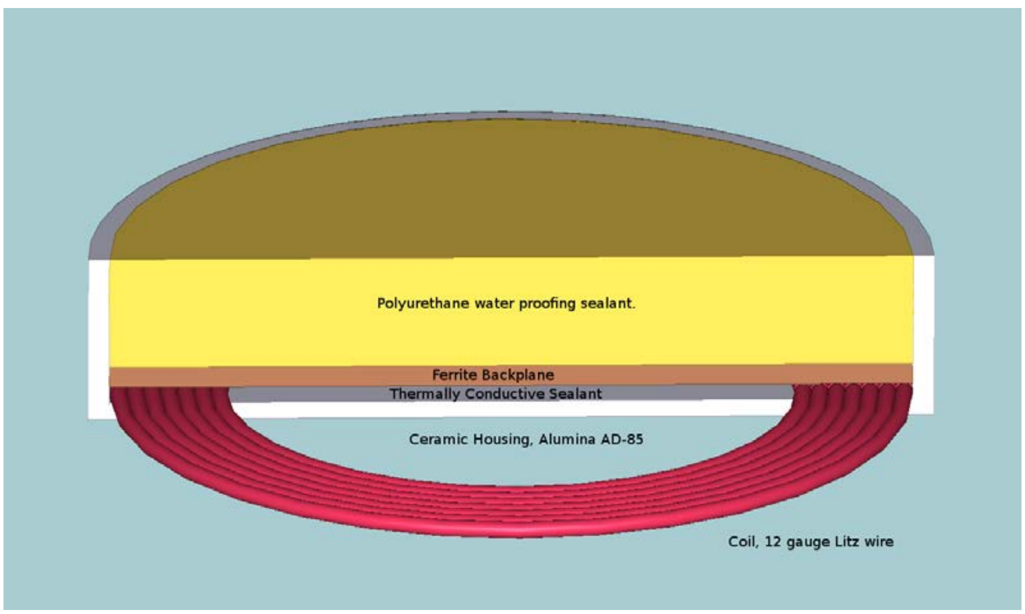

Figure 24. Prototype 1000-W charging coil.

This prototype design with the coil laid out on the surface of the alumina ceramic provides the maximum heat conductance and minimizes the stand-off distance of the coil relative to the receive coil. We did a thermal analysis for this configuration with the following parameters: (1) a disk diameter of 5 inches, (2) a ceramic thickness of 0.1 inch, and (3) an average encapsulant thickness of 0.05 inch. Both mineral oil and TC-2920F were considered for the encapsulant around the Litz wire. Only heat transfer through the face of the ceramic disk was considered. The results are shown in Table 6. The temperature differentials required for 100-W heat dissipation are 163 and 145 ºC for the mineral oil and TC-2920F, respectively.

Table 6. Prototype coil thermal analysis results.

Coil encapsulant	R_{coil}	$R_{alumina}$	R_{water}	R_{total}	ΔT for 100 W
Mineral oil	0.620	0.0125	0.99	1.63	163.00
TC-2920F urethane	0.147	0.0125	0.99	1.15	145.00

For testing the thermal dissipation of the prototype disk, SSC Pacific researchers prepared a ceramic disk with 30 5-**Ω** resistors in series to produce a resistance of 150 **Ω**. Three thermistors were installed at the locations indicated in Figure 25. The resistors and three thermistors were embedded in a layer of TC-2920F urethane about 0.25-inch thick, and a layer of ferrite plates were placed on top, with a fourth thermistor (D) located on top of the ferrite plates. Finally, an additional layer of TC-2920F urethane, about 0.75-inch thick, was poured on top to completely seal and waterproof the thermal disk assembly, shown in Figure 26.

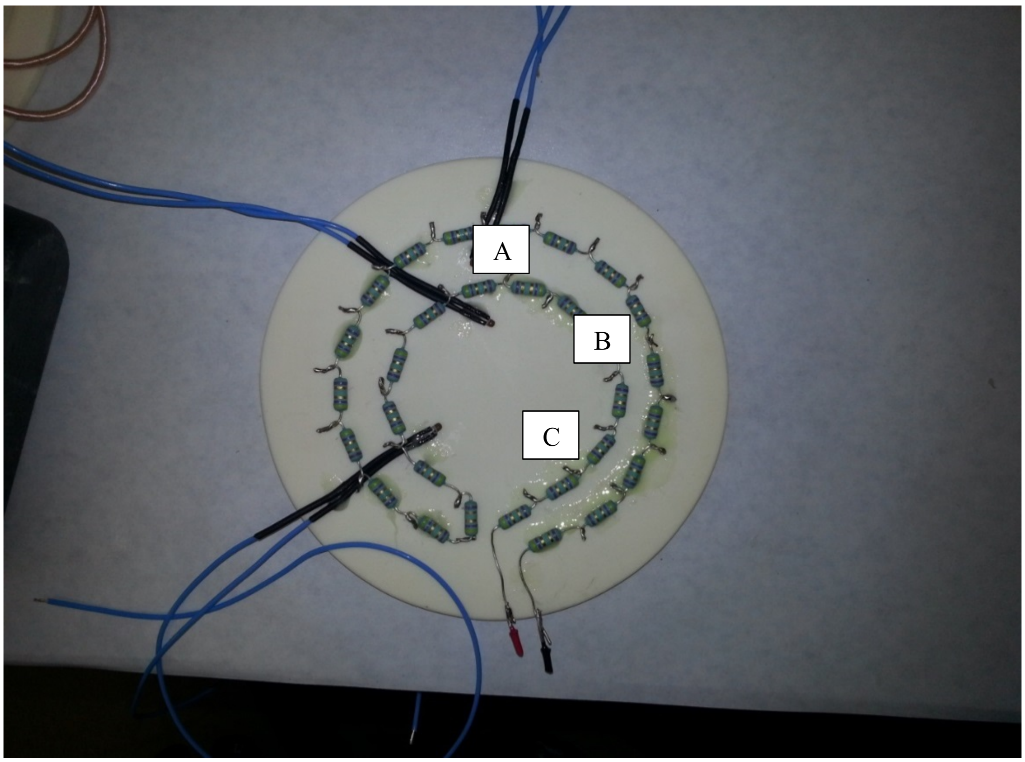

Figure 25. Ceramic disk with 30 resistors in series and thermistors A, B, C.

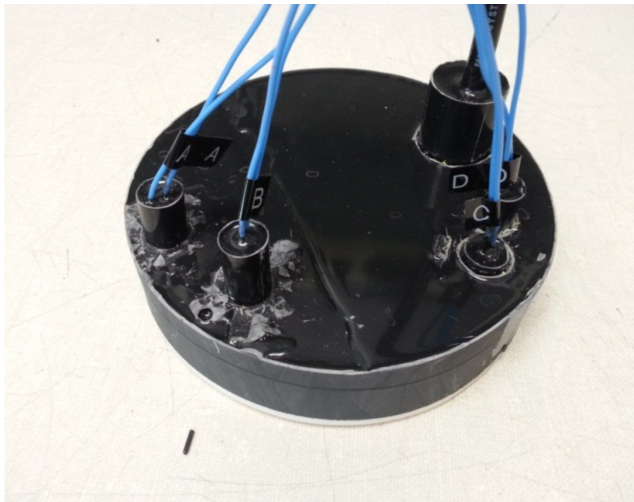

Figure 26. Thermal disk assembly.

We tested the thermal dissipation of this disk assembly using the previously discussed IR setup. The disk was placed in a shallow pan of water, about ½-inch deep, and 120 VAC was applied to the resistor chain, producing a 96-W thermal load. The backside of the disk was kept above water to allow the FLIR® camera capture unattenuated images. The thermistors provided internal temperatures at the locations indicated. The FLIR® image of the IR signal is shown in Figure 27. At the 96-W thermal load, the temperatures were elevated by 32.1, 27.9, 27.0, and 23.7 °C at locations A, B, C and D, respective-ly. Since the temperature rises are all on the order of 20 to 30 °C (which is reasonable for a power transfer system of this scale), one can conclude that the thermal dissipation is fully managed by the construction and materials used for the prototype coils.

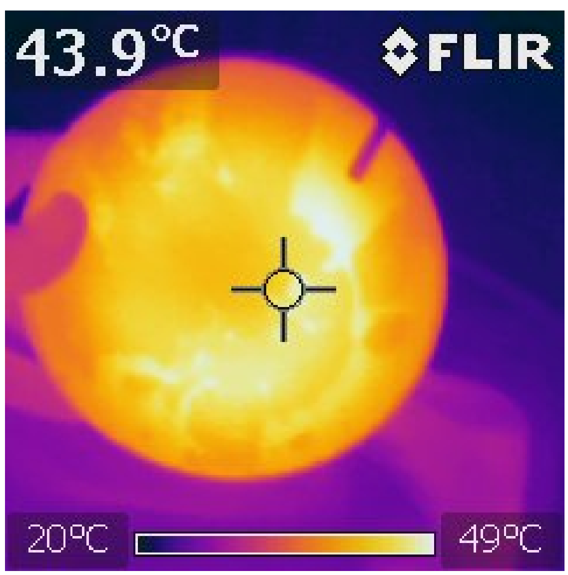

Figure 27. FLIR® Image of thermal disk at 96 W.

5. CONCLUSIONS

Heating the coils during power transmission drastically reduces the marine fouling of the wireless power transmission. The heating, with or without anti-foul coatings, will prevent significant marine fouling problems. The thermal dissipation can be satisfactorily managed by using the ceramic materials and construction techniques documented here while providing protection of the coils from the marine environment.

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14. ABSTRACT

This report describes the thermal effects and marine fouling on an undersea wireless power transfer system. The coils used in this wireless power transfer (WPT) experience elevated temperatures because of the resistive losses in the wire. Urethane and epoxy prevent water intrusion, but are thermal insulators and can lead to coil failure. Several different coating strategies to both protect the coils against seawater and dissipate the generated heat are investigated. In addition, the rise in temperature can increase the likelihood of marine biofouling on the exposed coil surfaces. A biofouling study on the wireless power transfer coils and whether there might be increased microbial growth as a result of the power transfer is also explored.

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15. SUBJECT TERMS

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